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Gamma-Ray Bursts as a Probe of the Epoch of Reionization

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Abstract. GRBs are expected to occur at redshifts far higher than the highest quasar redshifts so far detected. And unlike quasars, GRB afterglows may provide "clean" probes of the epoch of reionization because no complications (such as the presence of a strong Lyα emission line) or "proximity effects" (such as the Strömgren sphere produced by ionizing photons from the quasar) are expected. Thus NIR and optical observations of GRB afterglows may provide unique information about the epoch of reionization. In particular, the flux at wavelengths shortward of Lyα provides a direct measure of the density fluctuations of the IGM at the GRB redshift, while the flux at wavelengths longward of Lyα provides an integrated measure of the number of ionizing photons produced by stars in the host galaxy of the GRB up until the burst occurs. A comparison of the sizes of the Strömgren spheres produced by stars in the host galaxies of GRBs and by quasars then provides an estimate of the relative contributions of star formation and quasars to reionization. We use detailed calculations of the expected shape of the GRB afterglow spectrum in the vicinity of Lyα for GRBs at a variety of redshifts to illustrate these points.

1. Introduction

Exactly when and how the universe was reionized are two of the most important outstanding questions in astrophysical cosmology. The answers to these questions are of fundamental importance for understanding the moment of first light, the formation of the first galaxies, and the nature of the first generation of stars and of quasars,

Spectral observations of Lyα-emitting galaxies can be used as a probe of the epoch of reionization (Haiman 2002). However, such galaxies are faint and exceedingly rare (Hu et al. 2002), and the ability to draw inferences from the study of such Lyα-emitting galaxies is complicated by the necessity of disentangling the shape of the trough due to the red damping wing of the Lyα resonance from the (unknown) intrinsic profile of the Lyα emission line and the continuum spectrum at nearby wavelengths of the galaxy (Haiman 2002). In addition, scattering of the Lyα photons by a neutral IGM can broaden the line, reducing its visibility and further complicating the task of recovering the shape of the red wing of the Gunn-Peterson trough.

Observations of bright quasars at high redshifts can also be used as a probe of the epoch of reionization. As an example, the recently discovered bright quasar SDSS 1030+0524, which lies at $z = 6.28$, shows a distinct Gunn-Peterson

trough (Becker et al. 2001). The lack of any detectable flux shortward of $(1+z)\lambda_\alpha = 8850$ Å implies a strong lower limit ($x_H >\sim 0.01$) on the mean mass-weighted neutral fraction of the IGM at $z \approx 6$ (Fan et al. 2002). This suggests that the IGM is neutral beyond $z \sim 7$.

However, such quasars are rare ($\sim 10^{-3}$ deg^{-2}) and therefore difficult to find. And again, the ability to draw inferences from the study of such quasars is complicated by the necessity of disentangling the shape of the trough due to the red damping wing of the Lyα resonance from the (unknown) intrinsic profile of the bright Lyα emission line (Madau & Rees 2001; Cen & Haiman 2001).

Figure 1 places GRBs in a cosmological context. GRBs have several distinct advantages over Lyα-emission galaxies and quasars as a probe of the epoch of reionization:

- GRBs are by far the most luminous events in the universe, and are therefore easy to find.
- If GRBs are produced by the collapse of massive stars, as increasingly strong circumstantial evidence and tantalizing direct evidence suggests (see, e.g., Lamb 2000), 10-40% of GRBs may lie at very high redshifts ($z > 5$) (Lamb & Reichart 2000; see also Ciardi & Loeb 2000 and Bromm & Loeb 2002).
- Somewhat surprisingly, the infrared and near-IR afterglows of GRBs are detectable out to very high redshifts because of cosmological time dilation (Lamb & Reichart 2000).
- No "proximity effect" is expected for GRBs.
- GRB afterglows have simple power-law spectra and dramatically outshine their host galaxies, making it relatively easy to determine the shape of the red damping wing of the Lyα resonance.

2. Calculations

A stellar population with a Salpeter initial mass function extending from 0.1 to 120 $M_\odot$ produces ≈ 4000 ionizing photons per stellar proton over its lifetime. Assuming a (steady) SFR $\dot{M}_*$ and an age t_* for the star-forming episode, the total number $N_{\rm ion}$ of ionizing photons produced by the host galaxy is

$$N_{\rm ion} \approx 4.8 \times 10^{70} \left(\frac{f_{\rm esc}}{0.1}\right) \left(\frac{\dot{M}_*}{1000 M_\odot {\rm yr}^{-1}}\right) \left(\frac{t_8}{10^8 {\rm yr}}\right) \ {\rm ph}\ . \qquad (1)$$

Here $f_{\rm esc}$ is the fraction of the ionizing photons that are produced by the stars in the host galaxy and that escape from the galaxy. The fraction of ionizing photons that escape from nearby (low redshift) galaxies is $f_{\rm esc} \sim 0.1$. However, extinction is due primarily to dust, which may play a smaller role at redshifts $z \sim 7$ where the metallicity is expected to be far smaller. Pop III stars may produce a factor of ~ 10 more ionizing photons, but they are not expected to be a major contributor to the starlight from galaxies at redshifts $z = 7 - 9$.

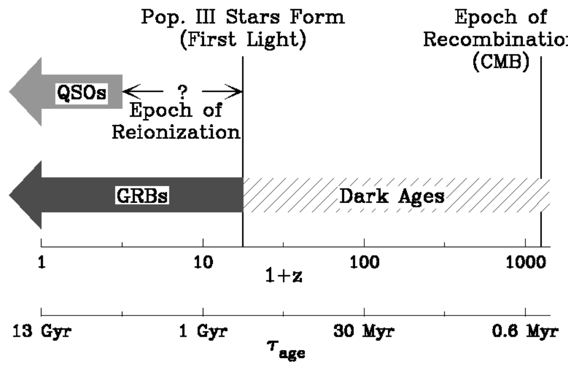

Figure 1. Cosmological context of very high redshift ($z > 5$) GRBs. Shown are the epochs of recombination, first light, and re-ionization. Also shown are the ranges of redshifts corresponding to the "dark ages," and probed by QSOs and GRBs. From Lamb (2000).

Consider a GRB host galaxy at redshift $z_{\rm GRB}$ with a (steady) SFR $\dot{M}_*$ and a star-forming episode of age t_*. We assume the source is embedded in an initially neutral IGM with a mean density $\langle \rho_{\rm IGM} \rangle = \Omega_b \rho_{\rm crit}(1 + z_{\rm GRB})^3$. The radius R_S of the ionized photons around a GRB host galaxy can then be written as $\dot{N}_{\rm ion} t_*$ where t_* is the age of the star-forming episode. We have equated the number of ionizing photons to the number of hydrogen atoms inside R_S. This is valid for low gas clumping factors and small ages, but recombinations can decrease the size of R_S for $C > 10$ and $t_* > 10^8$ yr. The results presented below take the UV spectrum of the GRB afterglow to have the form $F_\nu = F_0(\nu/\nu_0))^{-0.5}$.

3. Results

Figure 2 (upper panel) shows the near-IR spectrum of the afterglow of a GRB in a host galaxy lying at a redshift $z = 6.5$ in which stars have been forming at a rate $\dot{M}_* = 100 M_\odot$ yr^{-1} for $t_* = 10^8$ yrs. The nearly horizontal solid line near the top of the panel shows the adopted intrinsic spectrum, and the bottom solid curve shows the spectrum including absorption in the IGM and by the neutral atoms inside the 0.75 Mpc (proper) H II region surrounding the host galaxy of the GRB. The lower panel shows optical depth as a function of wavelength from within the H II region (short-dashed curve), from the neutral IGM outside the H II region (dotted curve), as well as from the sum of the two (solid curve). In both panels, the long-dashed curves describe an alternative, more realistic treatment of the residual H I opacity within the H II region (see text). The arrow indicates the wavelength of Lyα in the rest frame of the GRB and its host galaxy.

The shape of the afterglow spectrum of the GRB and the optical depth as a function of wavelength near the wavelength of Lyα in the rest frame of the GRB depend sensitively on (1) the clumpiness of the IGM, (2) the product of the star-formation rate $\dot{M}_\odot$ and the age $t_8$of the star-formation episode, and (3)

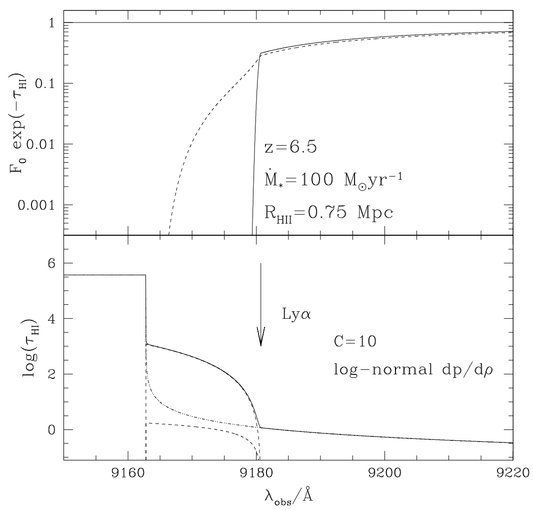

Figure 2. Near-IR spectrum of the afterglow of a GRB lying at $z = 6.5$.

redshift, because of the rapidly increasing density of the IGM with increasing redshift [$\rho_{\rm IGM} \propto (1+z)^3$]. Thus near-IR observations of GRB afterglows in the vicinity of the wavelength of Lyα in the rest frame of the GRB can provide unique information

4. Conclusions

We have shown that NIR and optical observations of GRB afterglows may provide unique information about the epoch of reionization. In particular, high-resolution near-IR observations of GRB afterglows can not only provide unique information about the properties of the IGM at very high redshifts, but also about the amount of star-formation that has occurred prior to the GRB in the host galaxy of the GRB.

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